Physics-based Modeling of Live Wildland Fuel Ignition Experiments in the FIST Apparatus

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Abstract: A computational study of the ignition of live Douglas-fir needles in the Forced Ignition and Flame Spread Test (FIST) apparatus is described. The study utilized the physics-based model WFDS. The Douglas-fir needles were approximated as fixed thermally thin fuel elements that undergo degradation based on Arrhenius-type equations. These fuel elements were subjected to radiation from a modeled heater with a surface heat flux of $50\ \mathrm{kW/m^2}$. Fuel moisture content (dry mass basis) of the needles ranged from 0% to 130%. The effect of evaporation at the time of ignition was included in the model setup. Ignition time, mass loss and heat release rate for the different moisture contents were computed. The simulated ignition times were comparable to the experimental findings. A linear correlation between ignition time and fuel moisture content, developed in the current modeling study, agreed well with a similar correlation developed from the experimental data.

1. Introduction

In wildland fires, fuel moisture content seems to play an important role in determining the time to ignition, a.k.a. ignition time, of live fuels but that role is still unclear [1]. The fuel moisture content (FMC) is defined as the ratio of mass of water to the dry fuel mass. Significant spread of wildfire is observed in vegetation comprised of live fuels with moisture content greater than 70% [2]. To understand the influence of fuel moisture content on the ignition time, piloted ignition experiments of cellulosic materials were performed and correlations between moisture content and ignition times were deduced [3, 4, 5]. In these works, woody materials were used as fuel and the common observation made was that ignition time increased with moisture content. They also found correlations for the ignition time that depended on moisture content and material properties of wood such as emissivity, thermal conductivity and density. There are several experimental studies [2, 6, 7] that used live fuels wherein the fuel moisture content evolves naturally over the course of an annual season. McAllister [2] performed piloted ignition experiments using the Forced Ignition and Flame Spread Test (FIST) apparatus on live fuels including Douglas-fir (*Pseudotsuga menziesii*) and lodgepole pine (*Pinus contorta*). These fuels were collected throughout the growing season, taking advantage of natural changes in moisture content and chemical composition. It was found that live fuels behaved as a thermally intermediate material with the suggestion of the existence of temperature gradients within the needles during the process of pyrolysis. A linear regression of ignition time against moisture content was predicted with a $74-80\%$ variability.

The aim of this study is to improve our understanding of ignition and combustion of live Douglas-fir needles in the recent experiments of McAllister *et al.* [2]. Here, the physics-based model WFDS [7], where solid fuels are represented by discrete particles, was used for computations. The fuel was assumed to undergo a two-stage endothermic decomposition process, including evaporation of water and pyrolysis, followed by an exothermic reaction of char oxidation. The pyrolyzate gases were assumed to be methane that reacted with air through a single-step chemical reaction that is mixing-controlled. Based on a range of FMC observed over different seasons in the experiments, a range of 0% to 130% was considered.

2. Computational Setup

The computational domain resembled the FIST apparatus (Fig. 1) used by McAllister *et al.* [2]. It consisted of a small-scale wind tunnel, infrared heater, coiled wire ignitor and a high precision mass balance. The Douglas-fir needles were placed on a sample holder which sat on the mass balance and were heated from above by the infrared heater with a uniform heat flux of $50\ \mathrm{kW/m^2}$. A laminar airflow over the sample pushed the pyrolysis gases from the heated sample over the ignitor held at $1000\ ℃$, thereby initiating ignition. Additional details of the apparatus are provided in [2].

As displayed in Fig. 2, the computational domain had dimensions 60cm in length (x), 30cm in width(y) and 11cm in height (z); the modelled wind tunnel dimensions were consistent with actual size A grid resolution of $120 \times 20 \times 22$ was used along the x, y and z directions, respectively. Within this domain, the walls of the wind tunnel were modeled to be inert and maintained at an ambient temperature of 293 K. A velocity inlet boundary condition was applied to the right entrance of the wind tunnel establishing a laminar airflow with a velocity of 1m/s through the wind tunnel. In this study, the Douglas-fir needles were approximated as fixed, thermally thin fuel elements uniformly distributed within a rectangular region with dimensions similar to the sample holder (9cm in length and 9cm in width). The vegetative dry and moist mass was also uniformly distributed among all fuel elements.

The infrared heater was modeled as a surface $9\mathrm{cm} \times 9\mathrm{cm}$ maintained at a temperature of 1050 K. To ignite the pyrolyzate gases in the simulations, a few non-reacting fuel particles held at a constant temperature of 1000 K were used. This modeled ignitor was located at a distance of 1.2 cm downstream of the fuel elements, centered 6mm off the bottom matching the experiments. Since Douglas-fir is a member of the *Pinaceae* family, the fuel elements underwent degradation modeled by an Arrhenius-type law with constants for pine needle combustion [9]. An initial total mass of fuel equal to 4g in all cases resulted in dry mass ranging from 4.0 to 1.74 as FMC was increased (Table 1). The needles had a density of $550\ \mathrm{kg/m^3}$ with a thickness of 0.48 mm. The physical and thermophysical properties of the needles were consistent with the experiments. The ignition time was analyzed based on the heat release rate value i.e., if the local value of heat release rate was greater than 200 kW/m^3, we assumed that ignition occurred in that region [10]. The ignition times observed from local value of heat release rate in simulation for varying FMC was compared with the ignition times visualized in experiments.

3. Results

As observed in the experiments, the ignition time increased with an increase in moisture content (Fig. 3). The modelled ignition times differed from the experimental times by 2-5s for fuel moisture contents between 90-120%. However, for a moisture content of 130%, the numerical values differed from experimental values by $8\mathrm{s}$. A linear regression of the predicted ignition times as a function of moisture content was fitted (Fig. 4). A comparison with linear regression obtained from experiments is also made. It is seen that the slope of the line obtained by the model is 1.28 times greater than the slope in the experiments. This difference between the slopes can have two reasons: (1) The effect of seasons is not modeled in the simulations; (2) Thermally intermediate characteristic of the needles is not taken into account in the models, as they are assumed to be thin.

In Fig. 5, the variation of total mass of the fuel with time is plotted. Here, the total mass includes dry and moist mass of Douglas-fir needles. In all cases, it was observed that the mass of the fuel begins to decrease significantly after the ignition time. For dry fuel with FMC = 0%, modelled ignition occurred at 6.8s and it was observed that the fuel mass decreased approximately linearly with time. However, in the other cases, this linearity was lacking.

Shown in Figs. 6 and 7, are the mass loss rates of dry vegetation and moisture versus time. In Fig. 6, it is seen that the dry fuel had a constant mass loss rate of $0.022\ \mathrm{g/s}$ from ignition time until all of the fuel was burnt. Also, the fuel with 60% FMC had a maximum peak mass loss rate of $0.036\ \mathrm{g/s}$ that occurred at $105\mathrm{s}$. For the cases with FMC larger than 60%, the peak mass loss rate occurred at a later instant in time ($> 105\mathrm{s}$) and had a value lower than $0.036\mathrm{g/s}$ owing to the presence of increased moisture mass. It was also observed that the mass loss rate flattened out for a brief period before increasing with time up to its peak value and the brief duration over which the mass loss rate remained nearly a constant, increased with FMC. The reason for this behavior can be understood from Fig. 7, where the MLR of moisture was plotted. At the time of ignition, the process of evaporation was more significant than the process of pyrolysis. With an increase in FMC, the process of evaporation occurred for a longer time period as displayed in Fig. 7 between times 40 and 160 s. The moisture mass loss rate changed gradually with time during this time. This change was reflected as a plateau in the mass loss rate for total mass in Fig. 6. Also the peak values of MLR for moisture lay in the range $0.014 - 0.016\ \mathrm{g/s}$ which is about 50% of the peak values of MLR for total mass. A total time of 450 s was taken to burn 4g of moist vegetation completely whereas the dry fuel burned completely in 200 s.

Fig. 8 shows the time evolution of heat release rate (HRR). The dry fuel has the highest HRR value of 0.77 kW which remained nearly constant during the course of the simulation. For the other cases with moisture, a peak value of HRR was attained at time instant ~ 100 s after ignition took place and this peak value decreased with an increase in moisture content.

4. Conclusions

A computational study was performed based on the piloted ignition experiments on live Douglas-fir needles in the Forced Ignition and Flame Spread Test apparatus. A particle based approach was used to model the burning of the needles wherein the particles were assumed to be thermally thin. The predicted ignition times compared well with the experimental observations. Also, a comparison is made between the linear correlation for ignition time predicted from simulation and that obtained from experiments and it is observed that the slope of the line obtained by the model is 1.28 times greater than the slope in the experiments.

5. References

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	Dry Mass (g)	Wet Mass (g)
1. Dry fuel (0%)	4.0	0.0
2. Moist fuel 60%	2.5	1.5
3. Moist fuel 90%	2.1	1.9
4. Moist fuel 100%	2.0	2.0
5. Moist fuel 110%	1.9	2.1
6. Moist fuel 120%	1.8	2.2
7. Moist fuel 130%	1.7	2.3

Table 1: Dry and wet mass distributions for various moisture contents considered in the simulation.

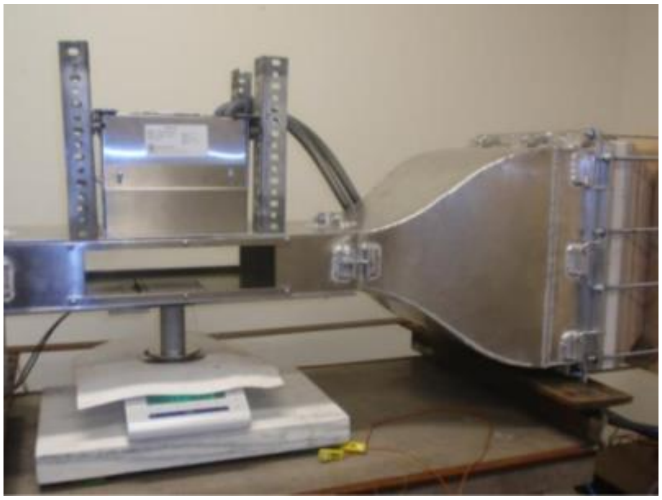

Figure 1: Forced ignition and flame spread apparatus used in experiments [1].

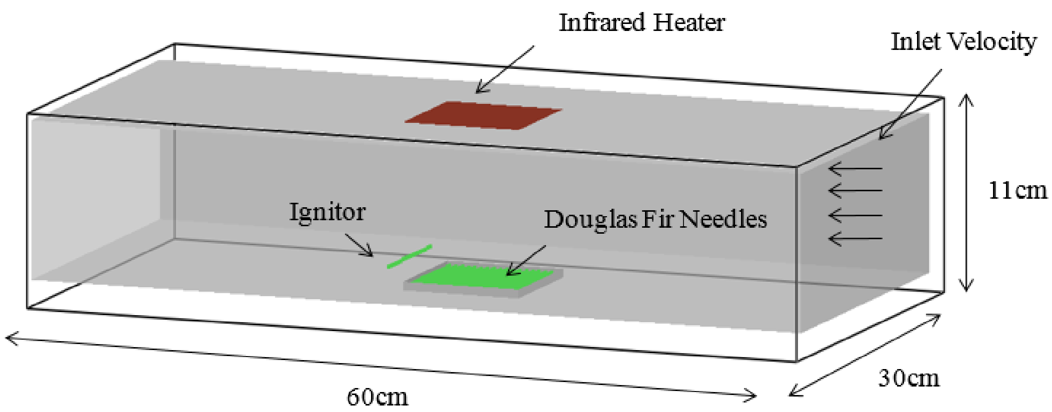

Figure 2: Computational domain (black outline) enclosing the modeled wind tunnel (gray volume). The green fuel elements represent Douglas fir needles.

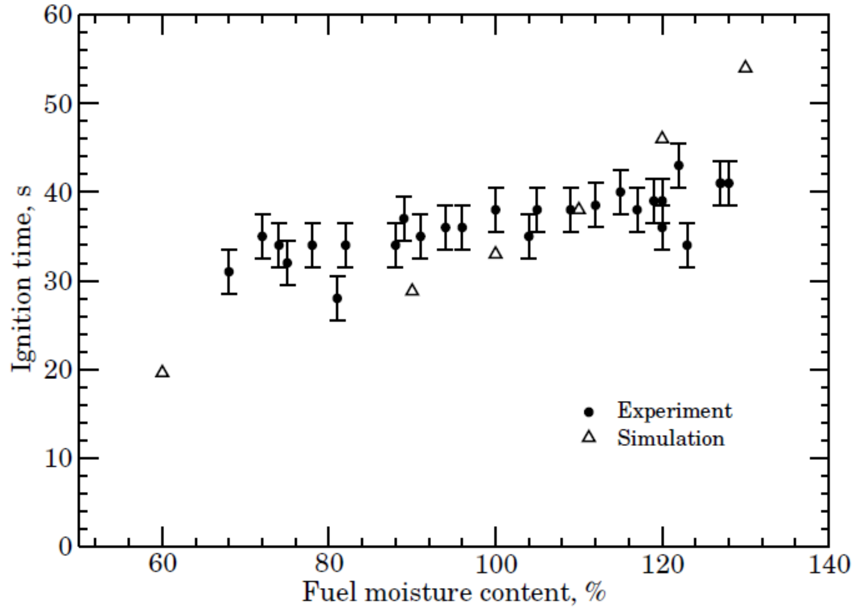

Figure 3: Ignition time versus fuel moisture content.

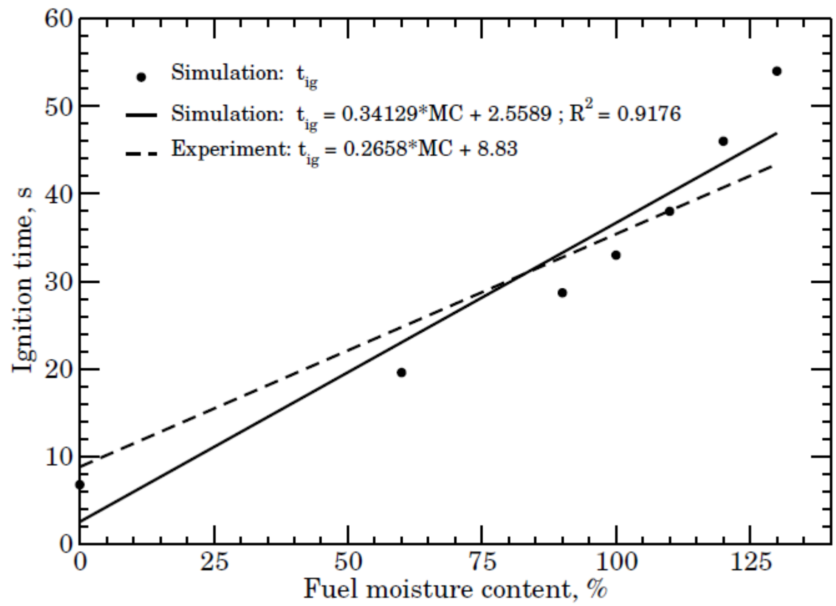

Figure 4: Ignition time versus fuel moisture content.

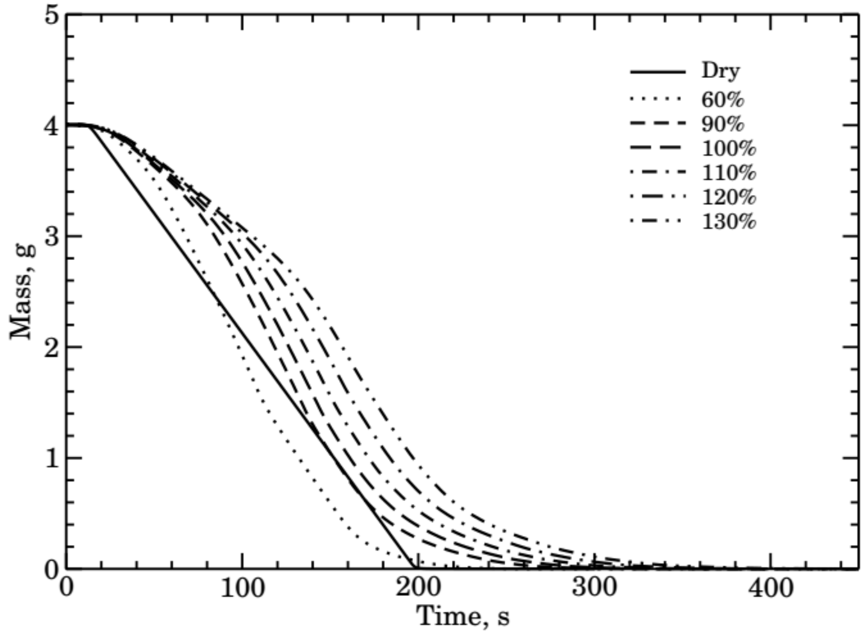

Figure 5: Time evolution of total mass of the Douglas fir needles for different moisture contents.

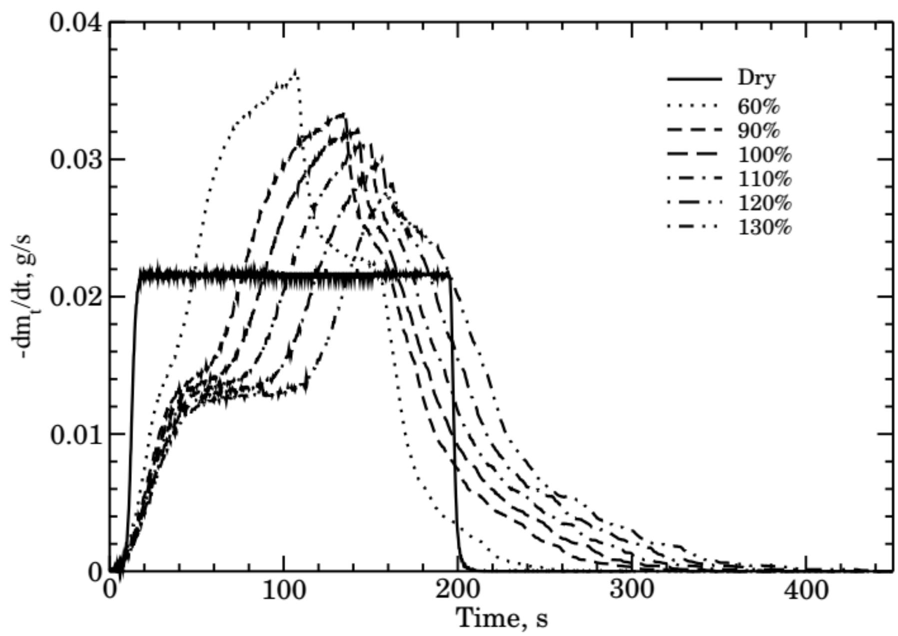

Figure 6: Time history of total mass loss rate for different moisture contents.

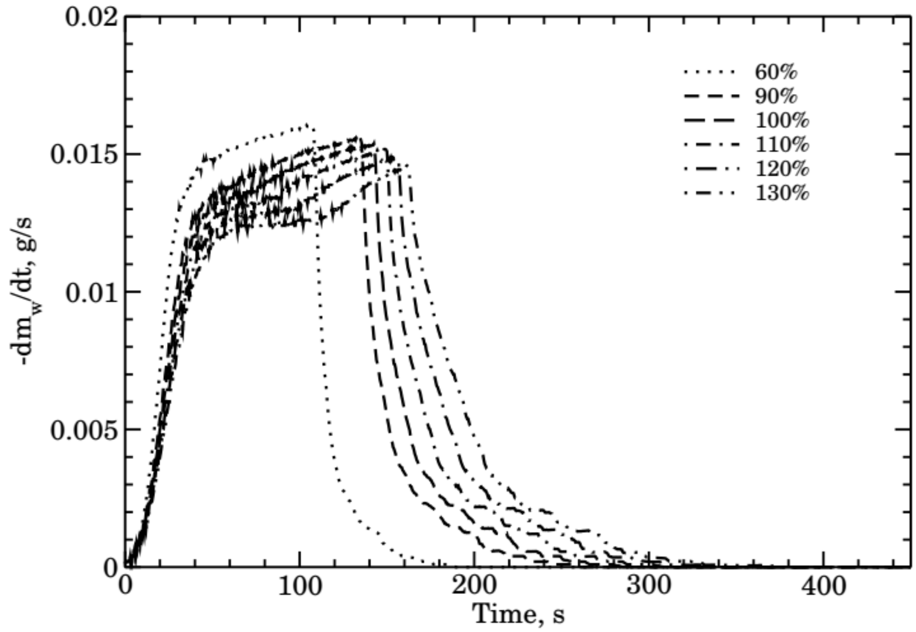

Figure 7: Time evolution of moisture mass loss rate.

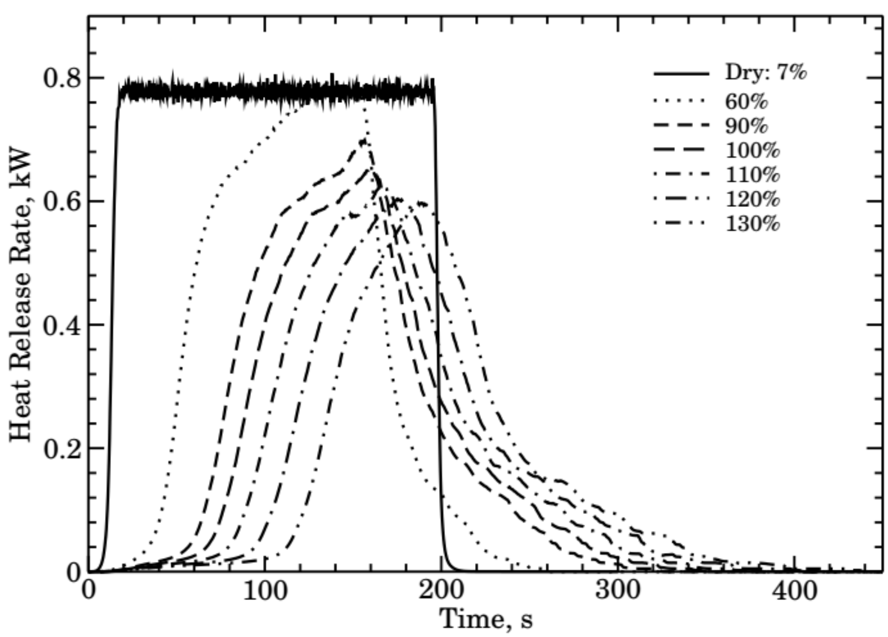

Figure 8: Variation of global heat release rate for different moisture contents.